Gearbox Fault Identification Under Non-Gaussian Noise and Time-Varying Operating Conditions

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Abstract. The Synchronous Average of the Squared Envelope (SASE) is very useful to visualise the periodicities in the instantaneous power of the machine due to damage. However, the SASE is sensitive to impulsive noise and the presence of non-synchronous damaged components and therefore provide unreliable representations of the condition of the gearbox under these conditions. Also, the instantaneous power is adversely affected by time-varying operating conditions. Impulsive noise and/or time-varying operating conditions can be encountered in the power generation (e.g. wind turbines) and mining industries (e.g. bucket wheel excavators). Hence, a method is proposed for impulsive data that were acquired under time-varying operating conditions. This method firstly estimates and removes the instantaneous power changes caused by the time-varying operating conditions, whereafter the Synchronous Geometric Average of the Squared Envelope (SGASE) is applied. A more numerically stable calculation of the SGASE is performed, which also provides further insights into its suitability for impulsive noise environments. The methodology is investigated on a bevel gearbox model that was simulated under time-varying operating conditions and an experimental dataset also acquired under time-varying conditions. The results indicate that the SGASE is to be preferred to the SASE for performing fault diagnosis in the presence of non-Gaussian noise.

Keywords: Gearbox fault diagnosis · Synchronous average of the squared envelope · Synchronous geometric average of the squared envelope

1 Introduction

Developing robust gearbox condition monitoring methods is very important for expensive rotating machines such as wind turbines. This ensures that the correct condition is

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inferred from the condition monitoring data, which enables the appropriate maintenance decisions to be made.

The instantaneous power of the vibration signal is rich with fault information that can be extracted by investigating its angle-domain statistics (e.g. synchronous average of the squared envelope) and its spectrum (e.g. squared envelope spectrum) (Borghesani and Antoni 2017).

However, rotating machines such as wind turbines operate inherently under time-varying operating conditions and the noise is often non-Gaussian, which impedes the application of the conventional techniques. Borghesani and Antoni (2017) indicated that the squared envelope spectrum is not robust to non-Gaussian noise and therefore proposed that the spectrum of the logarithm of the envelope should be used instead of the squared envelope spectrum in non-Gaussian noise conditions. Schmidt and Heyns (2020) proposed a method to Normalise the Amplitude Modulation caused by time-Varying Operating Condition (NAMVOC) that could impede the fault detection process.

The synchronous average of the squared envelope spectrum is especially powerful for gearbox condition monitoring, because it can be used for fault detection, fault trending and it is possible to visualise the modulation caused by the damaged components in the gearbox (e.g. it can help to distinguish between localised and distributed gear damage). However, the time-varying operating conditions and non-Gaussian noise impede its ability to provide a robust representation for the condition of the gearbox. Hence, the combination of two strategies is investigated to visualise the modulation caused by the damaged components in the gearbox. Firstly, the influence of the time-varying operating conditions is attenuated by using the NAMVOC method proposed by Schmidt and Heyns (2020), whereafter the synchronous geometric average of the squared envelope is used to present the modulation caused by the damaged components.

The layout of this paper is as follows: In the next section, Sect. 2, an overview of the considered methods is given, whereafter the methods are investigated on numerical bevel gearbox data in Sect. 3 and on experimental gearbox data in Sect. 4. Finally, conclusions are drawn in Sect. 5.

2 Gearbox Fault Diagnosis

Vibration-based fault diagnosis methods for gearboxes operating under time-varying conditions and non-Gaussian noise conditions are considered in this section.

2.1 The Influence of Time-Varying Operating Conditions

Time-varying operating conditions result in simultaneous amplitude and phase modulation (Stander et al. 2002, Chaari et al. 2012). The phase modulation can be attenuated by interrogating the signal in the angle domain, since the cyclostationary content attributed to damage is periodic in the angle domain. This can be performed by measuring or estimating the rotational speed of the system and using this information to transform the signal from the angle to the time domain through order tracking. Stander and Heyns (2006) indicated that if the instantaneous phase of the signal is estimated from a source that has a different transmission path as the vibration signal, phase distortion can occur. However, since the instantaneous power is interrogated in this signal, the influence of the phase distortion induced by varying speed conditions is not considered.

The amplitude modulation impedes the detection of gear damage as well as the estimation of the severity of the gear damage defects. Hence, a Normalisation of the Amplitude Modulation due to Varying Operating Condition (NAMVOC) method was proposed by Schmidt and Heyns (2020) to reduce the amplitude modulation due to varying operating conditions, while retaining the amplitude modulation caused by damage. The NAMVOC procedure assumes that the measured vibration signal x(t) can be decomposed as follows in terms of a modulation function N(t) and the raw signal q(t):

$$x(t) = N(t) \cdot q(t) \tag{1}$$

After N(t) is estimated, it can be used to calculate q(t) which is analysed for damage. The modulation function is estimated by using a moving median filter on the squared vibration signal as discussed by Schmidt and Heyns (2020). This filter ensures that the fault information is retained by the normalisation procedure. The modulation function N(t) is especially detrimental for vibration-based condition monitoring when it varies synchronously with the component-of-interest.

The application of the NAMVOC procedure is shown in Fig. 1 on the numerical bevel gear dataset described in Sect. 3. The vibration signal x(t), the rotational speed and load are presented in Fig. 1 for one of the measurements. Firstly, the NAMVOC procedure is applied on the signal with the resulting normalisation function N(t) being shown in Fig. 1 as well. The vibration signal is thereafter normalised to obtain a new signal q(t) = x(t)/N(t), which can be analysed for damage. The amplitude of the normalised signal is much less influenced by the time-varying operating conditions when compared to the raw vibration signal and therefore it is better suited for fault detection.

2.2 The Influence of Non-gaussian Noise

Non-Gaussian noise is attributed to the following two reasons in this work:

1. The operating environment of the rotating machine can result in non-Gaussian phenomena in the signal. For example, if the machine operates in an impulsive environment (e.g. mining industry (Wyłomańska et al. 2016)) or in the presence of electromagnetic interference, the signal would be leptokurtic.
2. Damaged machine components inherently result in non-Gaussian behaviour, because the signals tend to become more impulsive. Additionally, if the non-synchronous mechanical components are damaged, it would result in their corresponding signal components to be non-Gaussian with respect to the synchronous component under consideration.

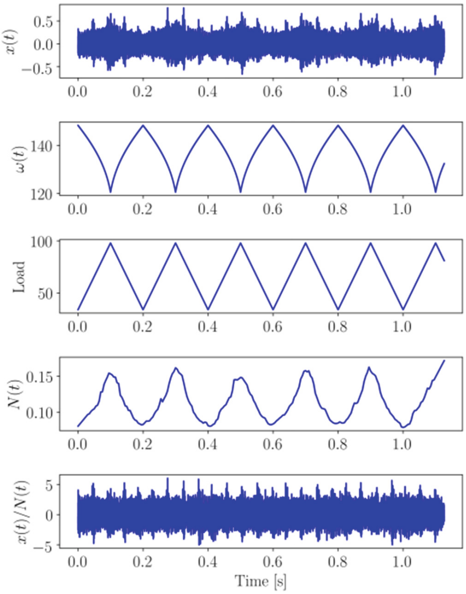


Fig. 1. Illustration of NAMVOC procedure for a signal x(t). The corresponding rotational speed ω(t), load and the estimated normalisation function N(t) are presented.

The Synchronous Average of the Squared Envelope,

$$s(\phi;\,\Phi) = \frac{1}{N_x}\sum_{k=0}^{N_x-1}|x(\phi + k\cdot\Phi)|^2 \tag{2}$$

is calculated for a specific cyclic period Φ (determined by the component under consideration) and is presented over a specific angular period range [0,φ). The number of rotations is denoted N_x and the angle variable is denoted φ. The SASE is especially adversely affected by non-Gaussian components in the vibration signal due to the fact that it utilises the sample average as an estimator of the central tendency of the instantaneous power. The sample average is unreliable for long-tailed distributions.

This can potentially be solved by considering the Synchronous Geometric Average of the Squared Envelope (SGASE)

$$g(\phi;\,\Phi) = \left(\prod_{k=0}^{N_x-1}|x(\phi + k\cdot\Phi)|^2\right)^{1/N_x} \tag{3}$$

instead of the SASE. If the SGASE is directly implemented with Eq. (3), it would be adversely affected by numerical underflow and lead to an erroneous estimation. Hence, the SGASE is rewritten as

$$g(\phi;\,\Phi) = \exp\left(\frac{1}{N_x}\sum_{k=0}^{Nx-1}\log|x(\phi + k\cdot\Phi)|^2\right) \tag{4}$$

which provides a numerically more stable implementation than Eq. (3). This representation also highlights why it is more suitable for non-Gaussian signals; the synchronous average of the logarithm of the squared envelope is calculated instead of the synchronous average of the squared envelope. According to Smith et al. (2019), the squared envelope of the signal that is estimated with the logarithm of the absolute of the signal, i.e.

$$SE_x(t) = \int \log |x(t)| p(x(t)) dx(t) \tag{5}$$

where p(x) is the probability density function of the signal x(t), converges for a broader range of distributions than using the conventional squared signal. Hence, the logarithm of the squared signal is expected to be more robust to non-Gaussian noise than the squared signal. Therefore, calculating averages in the logarithmic domain, would be more beneficial for analysing non-Gaussian signals and therefore the SGASE is expected to be more robust than the SASE.

The adverse influence of the time-varying operating and non-Gaussian noise conditions can therefore be attenuated in two sequential steps, namely, applying the NAMVOC procedure to remove the modulation functions due to the load and the speed and then by calculating the synchronous geometric average as opposed to the synchronous average. These methods are used in the next section on vibration data from a numerical gearbox model.

3 Bevel Gearbox Investigation

A numerical bevel gearbox model, originally presented in Mahgoun et al. (2016), was used to generate data under time-varying operating conditions. The equation of motion of the eight degree-of-freedom model is solved for the operating conditions shown in Fig. 2 with Newmark's algorithm.

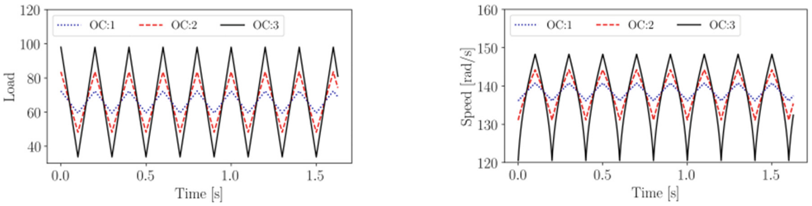
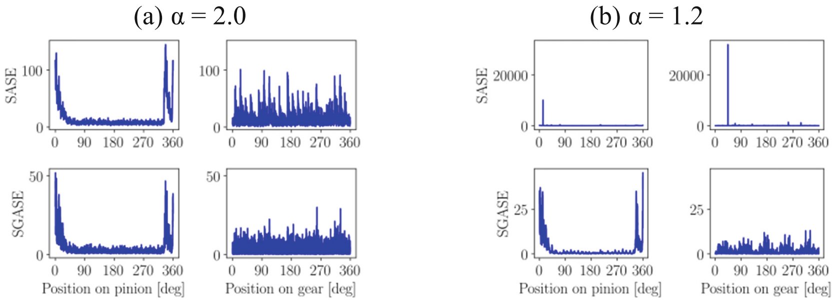


Fig. 2. The load and rotational speed for three Operating Condition (OC) states.

Non-Gaussian noise is investigated by adding r(t) to the vibration response of the structure. The noise, r(t), is sampled from a symmetric α-stable distribution with a mean of 0, a standard deviation of 1, and a parameter α which specifies its impulsivity. If α = 2, r(t) is Gaussian distributed, i.e. Gaussian noise is added to the signal, and as α becomes smaller, r(t) becomes more impulsive. Two distinct noise cases are investigated here; Gaussian noise (α = 2) and very impulsive noise with α = 1.2.

The measured signal is firstly normalised with the NAMVOC procedure whereafter the signal is order tracked. Thereafter, the SASE and SGASE are calculated for the case where the gear is healthy and the pinion contains localised damage. The results are presented in Fig. 3.


(a) $\alpha = 2.0$

(b) $\alpha = 1.2$

Fig. 3. Synchronous Average of the Squared Envelope (SASE) and the Synchronous Geometric Average of the Squared Envelope (SGASE) for α-stable noise with different levels of impulsivity.

For the Gaussian noise case in Fig. 3(a), the location of the damage on the pinion can clearly be seen for the SASE and SGASE. The SASE of the gear, however, contains very impulsive information which is attributed to non-Gaussian noise induced by the presence of the pinion damage. This means that the SASE cannot separate the contributions of the gear and the pinion. In contrast, the SGASE of the gear is much more uniform, which indicates that it is more robust to damage on the pinion.

For the non-Gaussian noise case in Fig. 3(b), it is impossible to infer the condition of gears by using the SASE. This is attributed to the fact that the SASE is very sensitive to non-Gaussian noise. In contrast, the SGASE is much more robust, with very similar results being obtained when compared to the Gaussian data case. Hence, the SGASE is capable of visualising the modulation caused by the damaged components with data that have non-Gaussian characteristics.

The robustness of the SGASE and the SASE are further investigated by calculating their Root-Mean-Square (RMS) for different fault severity levels of the pinion. The results are presented in Fig. 4 for the three operating conditions shown in Fig. 2.

The RMS of the SASE for the gear and the pinion have approximately the same values in Figs. 4(a) and (b) and are highly correlated, which means that it is impossible to effectively localise the damaged component. This has severe consequences for diagnosis as well as prognosis. In contrast, the RMS of the SGASE is much more robust, with the deteriorating pinion and the healthy gear being easily distinguished.

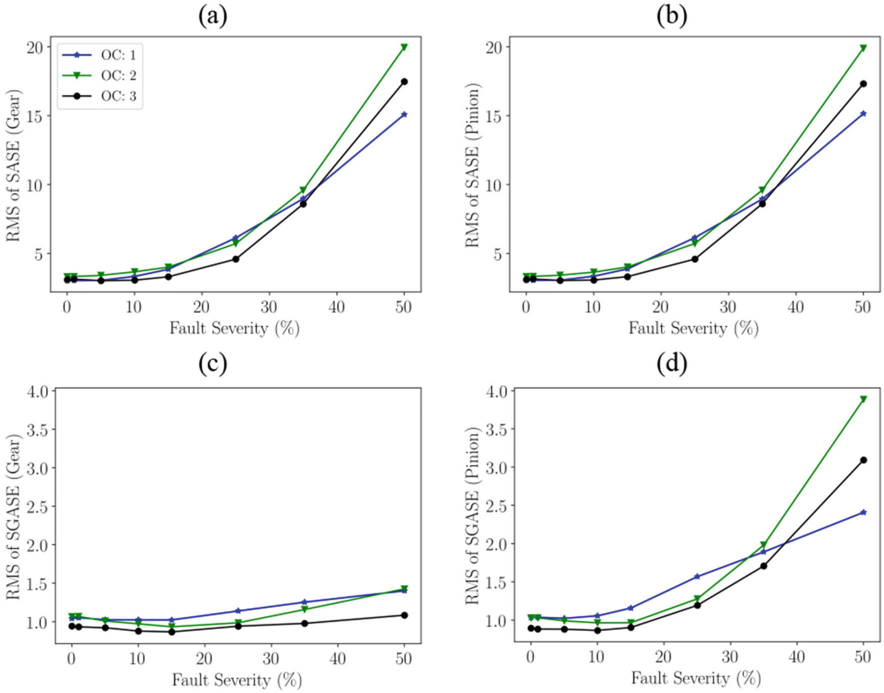


Fig. 4. The RMS of the SASE and the SGASE for different fault severities.

4 Experimental Investigation

The experimental setup presented in Fig. 5 is located in the Centre for Asset Integrity Management (C-AIM) laboratory at the University of Pretoria. It consists of an electrical motor, which drives the system, and an alternator which dissipates the rotational energy and three helical gearboxes. The centre gearbox, indicated as the test gearbox, is monitored for damage.

The test gearbox, which consists of a gear and a pinion, was damaged by seeding the gear with root damage. This gear was tested under the time-varying operating conditions shown in Fig. 5 until the gear failed, whereafter the test was stopped. The pinion was healthy for the duration of the test. Regular condition monitoring measurements were taken from the gearbox, with the axial component of a tri-axial accelerometer (located on the back of the gearbox) being used for monitoring. The rotational speed of the input shaft is estimated with an optical probe and a zebra tape shaft encoder.

The proposed procedure was implemented for four measurements with the results presented in Fig. 6. The vibration data from the gearbox contain much impulsive noise irrespective of the condition of the gearbox. The influence of this impulsive noise is clearly seen in the SASE of the gear in Fig. 6(a), with the gear damage at approximately 135 degrees not seen. In contrast the SGASE is robust to the impulsive noise, with the damage easily detected in Fig. 6(b). The SASE and SGASE perform similarly for the pinion in Fig. 6(a), because it is clear that the pinion is healthy.

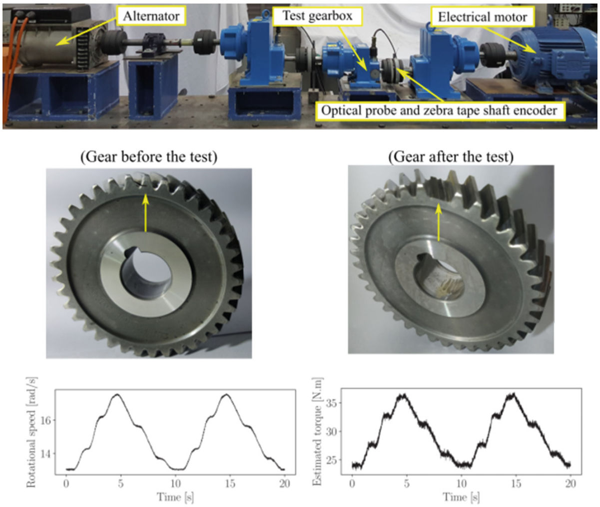


Fig. 5. The experimental setup, the gear before and after the test, and the operating conditions that are investigated in this work, are presented.

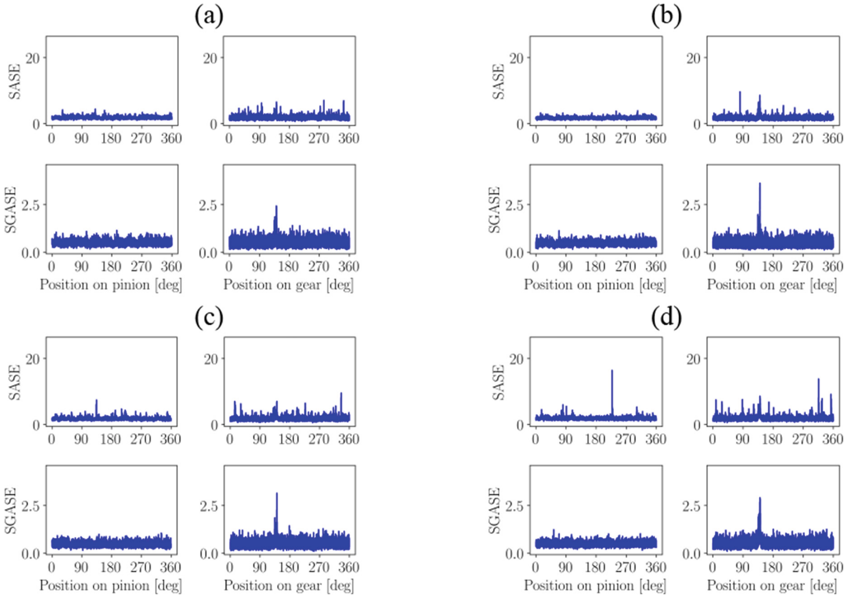


Fig. 6. The SASE and the SGASE are compared for four measurements from the experimental setup considered in this work. The damaged gear becomes progressively worse from measurements (a) to (d).

As the damage progresses from Fig. 6(a) to Fig. 6(d), the damaged component becomes more prominent in the SASE and SGASE. The damaged gear component can be identified with the SASE in Figs. 6(b) and (c), however, the corresponding SASE of the pinion contains much impulsive information, which makes it difficult to infer its condition. Hence, the SASE is very sensitive to non-Gaussian noise, while the SGASE is much more robust.

5 Conclusion

A procedure is proposed in this work for visualising the modulation caused by the damaged components of the gearbox from non-Gaussian data acquired under time-varying operating conditions. Firstly, the operating conditions are attenuated, whereafter the synchronous geometric average of the squared envelope is calculated. This method is investigated on a numerical and experimental dataset, with the results indicating that the synchronous geometric average of the squared envelope is much more robust to non-Gaussian noise than the synchronous average of the squared envelope and therefore can provide a more reliable representation for the condition of the gearbox.

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